Technical Summary of the National Hurricane Center Track and Intensity Models

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a. Introduction

The term "forecast model" refers to any objective tool used to generate a prediction of a future event, such as the state of the atmosphere. The National Hurricane Center (NHC) uses many models as guidance in the preparation of official track and intensity forecasts. The most commonly used models at NHC are summarized in Table 1.

Table 1. Summary of the mostly commonly used NHC track and intensity models. "E" refers to early and "L" refers to late in the timeliness column. "Trk" refers to track and "Int" refers to intensity the parameters forecast column.

Name/Description	ATCF ID	Type	Timeliness (E/L)	Parameters
Official NHC forecast	OFCL			Trk, Int
NWS/Geophysical Fluid Dynamics Laboratory (GFDL) model	GFDL	Multi-layer regional dynamical	L	Trk, Int
NWS/Hurricane Weather Research and Forecasting Model (HWRF)	HWRF	Mutlti-layer regional dynamical	L	Trk, Int
NWS/Global Forecast System (GFS)	GFSO	Multi-layer global dynamical	L	Trk, Int
National Weather Service Global Ensemble Forecast System (GEFS)	AEMN	Consensus	L	Trk, Int
United Kingdom Met Office model, automated tracker (UKMET)	UKM	Multi-layer global dynamical	L	Trk, Int
UKMET with subjective quality control applied to the tracker	EGRR	Multi-layered global dynamical	L	Trk, Int

Name/Description	ATCF ID	Type	Timeliness (E/L)	Parameters
Navy Operational Global Prediction System (NOGAPS)	NGPS	Multi-layer global dynamical	L	Trk, Int
Navy version of GFDL	GFDN	Multi-layer regional dynamical	L	Trk, Int
Environment Canada Global Environmental Multiscale Model	CMC	Multi-level global dynamical	L	Trk, Int
European Center for Medium-range Weather Forecasting (ECMWF) Model	EMX	Multi-layer global dynamical	L	Trk, Int
Beta and advection model (shallow layer)	BAMS	Single-layer trajectory	E	Trk
Beta and advection model (medium layer)	BAMM	Single-layer trajectory	E	Trk
Beta and advection model (deep layer)	BAMD	Single-layer trajectory	E	Trk
Limited area barotropic model	LBAR	Single-layer regional dynamical	E	Trk
NHC98 (Atlantic)	A98E	Statistical-dynamical	E	Trk
NHC91 (Pacific)	P91E	Statistical-dynamical	E	Trk
CLIPER5 (Climatology and Persistence model)	CLP5	Statistical (baseline)	E	Trk
SHIFOR5 (Climatology and Persistence model)	SHF5	Statistical (baseline)	E	Int
Decay-SHIFOR5 (Climatology and Persistence model)	DSF5	Statistical (baseline)	E	Int

Name/Description	ATCF ID	Type	Timeliness (E/L)	Parameters
Statistical Hurricane Intensity Prediction Scheme (SHIPS)	SHIP	Statistical-dynamical	E	Int
SHIPS with inland decay	DSHP	Statistical-dynamical	E	Int
Logistic Growth Equation Model	LGEM	Statistical-dynamical	E	Int
Previous cycle OFCL, adjusted	OFCI	Interpolated	E	Trk, Int
Previous cycle GFDL, adjusted	GFDI	Interpolated-dynamical	E	Trk, Int
Previous cycle GFDL, adjusted using a variable intensity offset correction that is a function of forecast time. Note that for track, GHMI and GFDI are identical	GHMI	Interpolated-dynamical	E	Trk, Int
Previous cycle HWRF, adjusted	HWFI	Interpolated-dynamical	E	Trk, Int
Previous cycle GFS, adjusted	GFSI	Interpolated-dynamical	E	Trk, Int
Previous cycle UKM, adjusted	UKMI	Interpolated-dynamical	E	Trk, Int
Previous cycle EGRR, adjusted	EGRI	Interpolated-dynamical	E	Trk, Int
Previous cycle NGPS, adjusted	NGPI	Interpolated-dynamical	E	Trk, Int
Previous cycle GFDN, adjusted	GFNI	Interpolated-dynamical	E	Trk, Int
Previous cycle EMX, adjusted	EMXI	Interpolated-dynamical	E	Trk, Int
Average of GHMI, EGRI, NGPI, and GFSI	GUNA	Consensus	E	Trk

Name/Description	ATCF ID	Type	Timeliness (E/L)	Parameters
Version of GUNA corrected for model biases	CGUN	Corrected consensus	E	Trk
Previous cycle AEMN, adjusted	AEMI	Consensus	E	Trk, Int
Average of GHMI, EGRI, NGPI, HWFI, and GFSI	TCON	Consensus	E	Trk
Version of TCON corrected for model biases	TCCN	Corrected consensus	E	Trk
Average of at least 2 of GHMI, EGRI, NGPI, HWFI, GFSI, GFNI, EMXI	TVCN	Consensus	E	Trk
Version of TVCN corrected for model biases	TVCC	Corrected consensus	E	Trk
Average of LGEM, HWFI, GHMI, and DSHP	ICON	Consensus	E	Int
Average of at least 2 of DSHP, LGEM, GHMI, HWFI, and GFNI	IVCN	Consensus	E	Int
FSU Super-ensemble	FSSE	Corrected consensus	E	Trk, Int

Forecast models vary tremendously in structure and complexity. They can be simple enough to run in a few seconds on an ordinary computer, or complex enough to require a number of hours on a supercomputer. Dynamical models, also known as numerical models, are the most complex and use high-speed computers to solve the physical equations of motion governing the atmosphere. Statistical models, in contrast, do not explicitly consider the physics of the atmosphere but instead are based on historical relationships between storm behavior and storm-specific details such as location and date. Statistical-dynamical models blend both dynamical and statistical techniques by making a forecast based on established historical relationships between storm behavior and atmospheric variables provided by dynamical models. Trajectory models move a tropical cyclone (TC) along based on the prevailing flow obtained from a separate dynamical model. Finally, ensemble or consensus models are created by combining the forecasts from a collection of other models. The following sections provide more detailed descriptions of the modeling systems and individual models most frequently used at NHC.

b. Early versus Late Models

Forecast models are characterized as either *early* or *late*, depending on whether they are available to the forecaster during the forecast cycle. For example, consider the 1200 UTC forecast cycle, which begins with the 1200 UTC synoptic time and ends with the release of an official forecast at 1500 UTC. The 1200 UTC run of the NWS/Global Forecast System (GFS) model is not complete and available to the forecaster until about 1600 UTC, an hour after the forecast is released. Thus, the 1200 UTC GFS would be considered a "late" model since it could not be used to prepare the 1200 UTC official forecast. Conversely, the BAM models are generally available within a few minutes of the time they are initialized. Therefore, they are termed "early" models. Model timeliness is listed in Table 1.

Due to their complexity, dynamical models are generally, if not always, late models. Fortunately, a technique exists to take the latest available run of a late model and adjust its forecast so that it applies to the current synoptic time and initial conditions. In the example above, forecast data for hours 6-126 from the previous (0600 UTC) run of the GFS would be smoothed and then adjusted, or shifted, so that the 6-h forecast (valid at 1200 UTC) would match the observed 1200 UTC position and intensity of the TC. The adjustment process creates an "early" version of the GFS model that becomes part of the most current available guidance for the 1200 UTC forecast cycle. The adjusted versions of the late models are known, largely for historical reasons, as "interpolated" models.

c. Interpreting Forecast Models

NHC provides detailed information on the verification of its past forecasts with a yearly verification report (http://www.nhc.noaa.gov/verification/verify3.shtml). On average, NHC official forecasts usually have smaller errors than any of the individual models. An NHC forecast reflects consideration of all available model guidance as well as forecaster experience. Therefore, users should consult the official forecast products issued by NHC and local National Weather Service Forecast Offices rather than simply looking at output from the forecast models themselves. Users should also be aware that uncertainty exists in every forecast, and proper interpretation of the NHC forecast must incorporate this uncertainty. NHC forecasters typically discuss forecast uncertainty in the Tropical Cyclone Discussion (TCD) product. NHC also prepares probabilistic forecasts that incorporate forecast uncertainty information (http://www.nhc.noaa.gov/aboutnhcprobs.shtml).

d. Statistical Models

Statistical models are based on established relationships between storm-specific information, such as location and time of year, and the behavior of historical storms. While these models provided key forecast guidance in past decades, today these models are most often used as benchmarks of skill against which more sophisticated and accurate models and the NHC official forecast are compared. Models that are less accurate than a simple statistical model are considered "unskillful" and models that are more accurate than statistical models are considered "skillful". Due to their simplicity, statistical models are among the quickest to run and are typically available to forecasters within minutes of initialization.

Climatology and Persistence Model (CLIPER5)

CLIPER5 is a statistical track model originally developed in 1972 and extended to provide forecasts out to 120 h (5 days) in 1998. As the name implies, the CLIPER5 model is based on climatology and persistence. It employs a multiple regression technique that estimates the relationships between several parameters of the active TC to a historic record of TC behavior to predict the track of the active TC. The inputs to the CLIPER5 include the current and past movement of the TC during the previous 12- and 24-hour periods, the direction of its motion, its current latitude and longitude, date, and initial intensity. CLIPER5 is now used primarily as a benchmark for evaluating the forecast skill of other models and the official NHC forecast, rather than as a forecast aid.

Statistical Hurricane Intensity Forecast (SHIFOR5)

SHIFOR5 is a simple statistical intensity model that uses climatology and persistence as predictors. In recent years it has been supplemented by the Decay-SHIFOR.

Decay-SHIFOR5

Decay-SHIFOR5 is a version of SHIFOR5 that includes a weakening component when TCs move inland. Decay-SHIFOR5 is most often used as a benchmark for evaluating forecast skill of other models and the official NHC intensity forecast. Unlike CLIPER5, which is not competitive with the more complex track models, decay-SHIFOR5 does provide useful operational intensity guidance.

e. Statistical-Dynamical Models

NHC91/NHC98 Models

The NHC98 (Atlantic) and NHC91 (east Pacific) models are statistical-dynamical models that employ the statistical relationships between storm behavior and predictors used by the CLIPER5, in addition to relying on forecast predictors of steering flow obtained from dynamical model forecasts, such as the deep-layer-mean GFS geopotential heights fields (averaged from 1000 to 100-mb). These models no longer produce competitive track guidance.

Statistical Hurricane Intensity Prediction Scheme (SHIPS)

The SHIPS model is a statistical-dynamical intensity model based on statistical relationships between storm behavior and environmental conditions estimated from dynamical model forecasts as well as on climatology and persistence predictors. Due to the use of the dynamical predictors, the average intensity errors from SHIPS are typically 10%-15% less than those from SHIFOR5. SHIPS has historically outperformed most of the dynamical models, including the GFDL, and SHIPS has traditionally been one of the most skillful sources of intensity guidance for NHC.

SHIPS is based on standard multiple regression techniques. The predictors for SHIPS include climatology and persistence, atmospheric environmental parameters (e.g., vertical wind shear, stability, etc.), and oceanic input such as sea surface temperature (SST) and upper-oceanic heat content. Many of the predictors are obtained from the GFS and are averaged over the entire forecast period. The developmental data from which the regression equations are derived include open ocean TCs from 1982 through the present. Each year the regression equations are re-derived based upon the inclusion of the previous year's data. Therefore, the weighting of the predictors can change from year to year. The predictors currently found to be most statistically significant are: the difference between the current intensity and the estimated maximum potential intensity (MPI), vertical wind shear, persistence, and the upper-tropospheric temperature. SHIPS also includes predictors from satellite data such as the strength and symmetry of convection as measured from infrared satellite imagery and the heat content of the upper ocean determined from satellite altimetry observations.

DeMaria M., and J. Kaplan, 1994: Sea surface temperature and the maximum intensity of Atlantic tropical cyclones. *J. Climate,* **7**, 1324–1334.

DeMaria, M., M. Mainelli, L.K. Shay, J.A. Knaff, and J. Kaplan, 2005: Further Improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting,* **20**, 531–543.

Decay-SHIPS

Decay-SHIPS is a version of SHIPS that includes an inland decay component. Since land interactions result in weakening, the Decay-SHIPS will typically provide more accurate TC intensity forecasts when TCs encounter or interact with land. Over open water with no land interactions, the intensity forecasts from Decay SHIPS and SHIPS will be identical.

Logistic Growth Equation Model (LGEM)

LGEM is a statistical intensity forecast model that uses the same input as SHIPS but in the framework of a simplified dynamical prediction system, instead of a multiple regression. The evolution of the intensity is determined by a logistic growth equation that constrains the solution to lie between zero and the TC's maximum potential intensity

(MPI), where the MPI is estimated from an empirical relationship with sea surface temperature (SST). The forecast of the maximum wind depends on the growth rate coefficient, which is estimated from a subset of the input to the SHIPS model. Ocean heat content and other parameters derived from geostationary satellites are also incorporated into the LGEM. An important difference from SHIPS is that the LGEM considers the variability in the environmental conditions over the length of the forecast while SHIPS does not; most of the SHIPS predictors are averaged over the entire forecast period, while the equivalent LGEM predictors are averaged only over the 24 hours prior to the forecast valid time. In addition, the MPI in the LGEM prediction is the instantaneous value, rather than the forecast period average used in SHIPS. These differences make the LGEM prediction more sensitive to environmental changes at the end of the forecast period, but also make the prediction more sensitive to track forecast errors. Since the LGEM model averages its predictors over a shorter time period, it is also better able to represent the intensity changes of storms that move from water to land and back over water relative to the SHIPS model.

f. Dynamical Models

Dynamical models are the most complex and most computationally expensive numerical models used by NHC. These models make forecasts by solving the physical equations that govern the atmosphere, using a variety of numerical methods and initial conditions based on available observations. Since observations are not taken at every location in the model domain, the model initial state can vary tremendously from the real atmosphere, and this is one of the primary sources of uncertainty and forecast errors in dynamical models. Errors in the initial state of a model tend to grow with time during the forecast, so small initial errors can become very large several days into the forecast period. It is largely for this reason that forecasts become increasingly inaccurate in time.

f.1. Global Dynamical Models

Global models are dynamical models with a domain that encompasses the entire planet. Table 2 provides details on the resolution and physics of the most common global models used at NHC.

Table 2. Description of the mostly commonly used global dynamical models at NHC.

Global Dynamical Model	Model Physics	Horizontal Grid Spacing (or equivalent if spectral)	Vertical Levels	Vertical Coordinates	Convective Parameterization	Data Assimilation
CMC GEM[1,2]	Hydrostatic Grid Point	0.30° latitude, 0.45° longitude (~33 km at 49° latitude)	80	Hybrid Sigma-Pressure	Kain-Fritsch (deep) Kuo-transient (shallow)	4-D Var
ECMWF[3,4,5]	Hydrostatic Spectral	~25 km	91	Hybrid Sigma-	Tiedtke	4-D Var

Global Dynamical Model	Model Physics	Horizontal Grid Spacing (or equivalent if spectral)	Vertical Levels	Vertical Coordinates	Convective Parameterization	Data Assimilation
				Pressure		
GFS[1,6]	Hydrostatic Spectral	~35 km (through FHR 180) ~80 km (FHR 180-384)	64	Hybrid Sigma-Pressure	Simplified Arakawa-Shubert	3-D Var; GSI/GDAS Analysis[6]
NOGAPS[1]	Hydrostatic Spectral	~55 km	30[1]	Hybrid Sigma-Pressure	Emmanuel	3-D Var; NAVDAS Analysis
UKMET[3,7,8]	Non-Hydrostatic Grid Point	0.40° latitude, 0.50° longitude (~40 km in mid latitudes)	50	Hybrid Sigma-Pressure	Gregory/ Rowntree	4-D Var

1 MetEd, 2007: *Operational Models Matrix*, University Corporation for Atmospheric Research. <http://www.meted.ucar.edu/nwp/pcu2/>

2 Macpherson, S. et al., 2009: Recent Developments in Assimilation of Satellite Data in MSC 4D-Var Analysis and Forecast System. Meteorological Research Division, Environment Canada. <http://www.eumetsat.int/groups/cps/documents/document/pdf_conf_p_s12_75_macphers_v.pdf>

3 Untch, Agathe, 2009: *Adiabatic Formulation of the ECMWF Model*, European Center for Medium Range Forecasting. <http://nwmstest.ecmwf.int/newsevents/training/meteorological_presentations/ppt/NM/Adiabatic.ppt>

4 Bechtold, Peter, C. Jakob, and D. Gregory, 2009: *Numerical Weather Prediction Parameterization of Diabatic Processes: Convection II – The Parameterization of Convection*, European Center for Medium Range Forecasting <http://www.ecmwf.int/newsevents/training/meteorological_presentations/ppt/PA/conv2.ppt>

5 European Center for Medium Range Forecasting, 2007: *ECMWF Products*. <http://www.ecmwf.int/products/>

6 MetEd, 2007: *GFS Introduction*, University Corporation for Atmospheric Research. <http://www.meted.ucar.edu/nwp/pcu2/avintro.htm>

7 UK Met Office, n.d.: *Atmospheric numerical model configurations.* Retrieved 8 July 2009 <http://www.metoffice.gov.uk/science/creating/daysahead/nwp/um_config.html>

8 UK Met Office, n.d.: *Observations – monitoring and quality control.* Retrieved 8 July 2009 <http://www.metoffice.gov.uk/science/creating/first_steps/obs_qc.html>

Canadian Meteorological Centre (CMC) Global Environmental Multiscale Model (GEM)

The CMC runs the global version of their GEM model through 144 hours at 1200 UTC and through 240 hours at 0000 UTC. Highlights of the resolution and physics of the CMC GEM are available in Table 2. In June 2009, the CMC GEM converted to a hybrid vertical coordinate system that is terrain-following in the boundary layer (sigma) and becomes purely isobaric (pressure) near the tropopause, a structure similar to that used by the other global models noted in Table 2. Also in June 2009, the upper boundary of the model was raised from 10 mb (32 km) to 0.1 mb (64 km). This change permits the incorporation of more satellite observations into the initial model analysis. This latest incarnation of the GEM is referred to as the GEM "Meso-Strato" version or simply "GEM-Strato". The CMC's GEM, like the ECMWF and UKMET, employs a four-dimensional data assimilation scheme (4-D Var) that allows better assimilation of offtime (non-synoptic) observations, particularly from satellite data. Further information about the CMC GEM model can be found on the University Corporation for Atmospheric Research (UCAR) MetEd Individual Numerical Weather Prediction (NWP) Model Matrix webpage:

http://www.meted.ucar.edu/nwp/pcu2/

The following link provides details on recent updates to the CMC's GEM model:

http://www.smc-msc.ec.gc.ca/cmc/op_systems/recent_e.html

The CMC GEM does not make accommodations to its initial analysis of environmental conditions for TCs. Prior to 2009, the CMC GEM had a tendency to over-forecast genesis of TCs. The recent changes to the model upper boundary are believed to decrease the false alarm ratio for TC genesis, particularly at day 3 and beyond in the forecast period.

MetEd, 2006: *GEM Regional Model Vertical Coordinate System*, University Corporation for Atmospheric Research. <http://www.meted.ucar.edu/nwp/pcu2/gemvert.htm>

MetEd, 2009: *Canadian Global and Regional GEM Upgrades: 22 June 2009*, University Corporation for Atmospheric Research. <http://www.meted.ucar.edu/nwp/pcu2/GEM_20090622.htm>

European Center for Medium-range Weather Forecasts (ECMWF) Model

Developed and maintained by an international organization supported by 28 European member states, the ECMWF model is the most sophisticated and computationally expensive of all the operational global models currently used by NHC. The ECMWF system provides forecasts out to 240 hours at 0000 UTC and 1200 UTC. Some of the specifications of the model are noted in Table 2. Due to the model's complexity/resolution, data assimilation, and the operational requirements of the member states, the ECMWF model is among the latest-arriving dynamical model guidance to NHC. The ECMWF, like the GFS and NOGAPS, is a spectral model that calculates parameters using spherical harmonics instead of grid points. More information about the technical specifications of the ECMWF model can be found here:

http://www.ecmwf.int/products/forecasts/guide/

The ECMWF does not alter its initial fields for TCs. Despite this, it has shown skill in forecasting TCs. Beyond the good medium-range TC track prediction skill of the ECMWF model, its high spatial resolution has shown potential for useful intensity and wind field structure forecasting.

U.S. National Weather Service Global Forecast System (GFS)

Developed and maintained by the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP), the GFS is run four times per day (0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC) out to 384 hours. Table 2 provides some of the technical specifications of the GFS model. Of note, the horizontal resolution of the GFS model is degraded beyond the first 180 hours of its forecast period. GFS runs obtain their initial conditions from a three-Dimensional Variational (3-D VAR) Gridpoint Statistical Interpolation (GSI). More details about the GFS model can be found on the UCAR/MetEd Individual Numerical Weather Prediction (NWP) Model Matrix webpage:

http://www.meted.ucar.edu/nwp/pcu2/

The following link provides information on recent updates to the GFS model:

http://www.emc.ncep.noaa.gov/modelinfo/

The GFS makes a special accommodation for TCs in its initial fields by relocating the globally analyzed TC vortex in the first-guess field to the official NHC position. An assimilation of the available data is then performed to create the initial state. The globally analyzed vortex is, however, often an incomplete representation of the true TC structure. For this reason, the GFS is typically more suited to producing track and outer wind structure forecasts than to producing intensity forecasts.

Navy Operational Global Atmospheric Prediction System (NOGAPS)

The NOGAPS model is run out to 180 hours four times a day (0000 UTC, 0600 UTC, 1200 UTC, 1800 UTC). Some of its operational specifications are highlighted in Table 2. The hybrid sigma-pressure vertical coordinate configuration used by the NOGAPS results in approximately six terrain-following sigma levels below 850-mb and the remaining 24 levels occurring above 850-mb at near-pressure surfaces. Further information about the NOGAPS can be found on the UCAR/MetEd Individual NWP Model Matrix webpage:

http://www.meted.ucar.edu/nwp/pcu2/

The NOGAPS model inserts an artificial TC vortex into its initial fields to more accurately depict the current intensity and location of TCs. The artificial vortex is created by adding synthetic ("bogus") data points to the observational data which are then incorporated during the data assimilation process. Like other global models, the NOGAPS model cannot provide very skillful intensity forecasts but can provide skillful track forecasts.

United Kingdom Meteorological Office (UKMET) Model

The UKMET model is run twice daily at 0000 UTC and 1200 UTC producing forecasts out to 144 hours. Intermediate runs initialized around the 0600 UTC and 1800 UTC data cycles are run at approximately 1300 UTC and 0100 UTC, but only produce forecasts to 48 hours. Table 2 provides the current resolution and operational specifications of the UKMET. Unlike the other models noted in Table 2, the UKMET attempts to explicitly calculate the vertical accelerations in the atmosphere rather than rely on the hydrostatic primitive equations.

Like the NOGAPS, the UKMET inserts a synthetic TC vortex into its initial fields based on the current intensity and position of the TC. The UKMET typically provides useful TC track forecasts but has limited ability to produce skillful intensity forecasts.

Limited Area Sine Transform Barotropic (LBAR) Model

LBAR is a simple two-dimensional dynamical track prediction model. It solves the shallow-water wave equations initialized with vertically averaged (850-200 hPa) winds and heights from the GFS global model. An idealized symmetric vortex and a constant wind vector (equal to the initial storm motion vector) are added to the GFS global model analysis to represent the TC circulation. The model equations are solved using a spectral sine transform technique over an area near the TC. The lateral boundary conditions are obtained from the GFS forecast. LBAR includes no horizontal gradients in temperature (and as a consequence, no vertical wind shear), making the LBAR a relatively poor performer beyond 1-2 days or outside of the deep tropics.

Vigh, J., S.R. Fulton, M. DeMaria, and W.H. Schubert, 2003: Evaluation of a multigrid method in a barotropic track forecast model. *Mon. Wea. Rev.*, **131,** 1629-1636.

f.2. Regional TC Dynamical Models

Regional TC dynamical models are dynamical models with domains that encompass the area of influence of a TC while obtaining their boundary conditions from a global dynamical model. Table 3 provides details on the operational characteristics and resolution of the nested TC dynamical models primarily used at NHC.

Table 3. Description of the most commonly used nested TC dynamical models at NHC.

Nested TC Dynamical Model	Global Model Boundary Conditions	Horizontal Grid Spacing	Vertical Levels	Coupled Ocean Model(s)
GFDL[1]	GFS	75° x 75° Outer grid ~30 km 11° x 11° Middle grid ~10 km 5° x 5° Inner grid ~5km	42	Atlantic: 3-D POM Pacific: 1-D POM
GFDN[2]	NOGAPS	75° x 75° Outer grid ~30 km 11° x 11° Middle grid ~10 km 5° x 5° Inner grid ~5km	42	Atlantic: 3-D POM Pacific: 3-D POM
HWRF[3,4]	GFS	75° x 75° Outer grid ~27 km Inner grid ~ 9km	42	Atlantic: 3-D POM Pacific: None

1 Bender, M.A., I. Ginis, R. Tuleya, B. Thomas, and T. Marchok, 2007: The operational GFDL coupled hurricane-ocean prediction system and summary of its performance. *Mon. Wea. Rev.*, **135**, 3965-3989.

2 Skupniewicz, C., 2009: *GFDN 2009*. 2009 METSAT and Tropical Cyclone Conference. Honolulu, HI. <http://metocph.nmci.navy.mil/jtwc/TCC/tcc_presentations/Thursday/13-Skupniewicz.ppt>
3 Environmental Modeling Center, 2008: *HWRF Homepage*. National Weather Service/National Centers for Environmental Prediction. <http://www.emc.ncep.noaa.gov/HWRF/index.html>
4 Tuleya, R., et al., 2008: *Hurricane Model Transitions to Operations at NCEP/EMC: A Joint Hurricane Testbed Program*. 63rd Interdepartmental Hurricane Conference. Charelston, SC. <http://www.ofcm.gov/ihc09/Presentations/Session06/s06-02tuleya.63rdihc.ppt>

NWS Geophysical Fluid Dynamics Model (GFDL) Hurricane Model

The GFDL Hurricane Model is a limited-area, triply-nested grid-point model designed specifically for TC prediction. This grid configuration along with other technical specification for the GFDL can be found in Table 3. The GFDL is run for up to four TCs every six hours out to 126 hours as requested by NHC and CPHC. The high resolution of the GFDL allows it to resolve relatively small-scale features within a TC such as the eye and eyewall. Still, even the GFDL is not able to fully resolve the highly complex structure of a TC. The GFDL is coupled with a high-resolution version of the Princeton Ocean Model (POM), which allows TC-induced ocean modification, such as sea-surface temperature cooling, and partially accounts for the feedback of the modified ocean on the TC. In the Atlantic, the POM is three dimensional with 23 vertical levels. In the eastern North Pacific where ocean currents and sea surface temperature gradients are more predictable, only a one-dimensional POM is used. In the GFDL analysis, the GFS TC vortex is replaced with an axisymmetric vortex spun up in a separate model simulation. The axisymmetric vortex model utilizes TC specifications as provided by NHC forecasters.

Since the horizontal resolution of the GFDL is sufficiently high to represent *some* of the inner core TC structure, the GFDL model has up to now been the only purely dynamical model that can provide both skillful intensity and track forecasts (http://www.nhc.noaa.gov/verification/verify3.shtml).

While it is still used operationally, there are no plans to further develop the GFDL Hurricane Model. However, the GFDN model, which currently has resolution and physics similar to the GFDL, will continue to be improved. See the section below for details on the GFDN.

Bender, M.A., I. Ginis, R. Tuleya, B. Thomas, and T. Marchok, 2007: The operational GFDL coupled hurricane-ocean prediction system and summary of its performance. *Mon. Wea. Rev.*, **135**, 3965-3989.

U.S. Navy Version of the GFDL Hurricane Model (GFDN)

The U.S. Navy also runs a version of the GFDL model (GFDN) that obtains its initial conditions, aside from the TC vortex, and its boundary conditions from the NOGAPS model. The physics, resolution, and ocean coupling of the GFDN were updated in late 2008 to be mostly consistent with the NWS version of the GFDL. For the ocean coupling in the Pacific, fields from the Navy Coupled Ocean Data Assimilation (NCODA), which is a high-resolution ocean analysis, are used to initialize the POM as opposed to NCEP ocean analyses that are used for the GFDL model. Currently the

GFDN's ocean coupling is being converted from 1-D to 3-D in the eastern North Pacific basin, and later in 2009 the ocean should be initialized by NCODA. Additional resolution and physics upgrades are planned for the GFDN hurricane model during the next couple of years.

Hurricane Weather Research and Forecasting Model (HWRF)

The Hurricane Weather Research and Forecast (HWRF) model was developed by the National Centers for Environmental Prediction (NCEP) Environmental Modeling Center and implemented operationally in 2007. The HWRF is run for up to four TCs every six hours out to 126 hours as requested by NHC and CPHC. The HWRF uses a nested grid system that is described along with other technical specifications in Table 3. The GSI 3-D Var data assimilation scheme uses a first guess vortex based on the 6-hour forecast from the previous HWRF run to produce an initial representation of the TC that matches intensity and structure parameters provided by NHC forecasters. The HWRF is coupled to the three dimensional POM in the Atlantic basin to better represent the interaction of the atmosphere and ocean in the TC environment, an important factor in TC intensity prediction. Further details on the HWRF can be found on the following webpage:

http://www.emc.ncep.noaa.gov/HWRF/index.html

g. Ensembles and Consensus Forecasts

Consensus forecasts are obtained by combining the forecasts from a collection (or "ensemble") of models, where the ensemble can either consist of multiples runs of a single model or runs from different independent models. The simplest way to form a consensus is to average the output from each member of the ensemble, e.g., one computes the mean of each member's predicted latitudes and longitudes of the TC center at some forecast time. At NHC, some of the more commonly used consensus forecasts are GUNA, TVCN, FSSE, and ICON, which are described below. On average, consensus forecasts are more accurate than the predictions from their individual model components. The variation or spread of the ensemble members can provide a measure of forecast uncertainty.

Taking the consensus approach a step farther, "corrected" consensus models assign different weights to each member model in an attempt to account for biases of each individual member model. One limitation of the "corrected" consensus technique occurs when the past performance of the member models does not accurately represent their present performance (e.g., if major changes are made to a member model between successive hurricane seasons). Some of the commonly used "corrected" consensus forecasts at NHC include FSSE, TVCC, and TCCN.

Single-model ensembles are multiple predictions from the same starting time for a given model, using different initial conditions. This type of ensemble accounts for the uncertainties in the initial state of the atmosphere. Even among single-model ensembles, a simple average of its members (i.e., the ensemble mean) often produces a more skillful forecast than any individual ensemble member, since errors associated with the individual forecasts tend to be canceled out. However, the ensemble mean often smoothes out the finer-scale details associated with the individual ensemble member forecasts. In most cases, the ensemble runs are made at relatively coarse resolution compared to the parent model. Ensembles from a single model have not proven to be as useful for TC forecasting as ensembles constructed from different independent models.

GUNA

GUNA is a simple track consensus computed by averaging the forecast latitudes and longitudes from the GHMI (interpolated GFDL), EGRI (interpolated UKMET with subjective quality control), NGPI (interpolated NOGAPS), and GFSI (interpolated GFS) models. All four member models must be available at a given forecast lead time to compute GUNA for that particular time.

CGUN

CGUN is a version of GUNA that is corrected for model biases. The biases are derived statistically, based on parameters known at the start of the forecast, such as model spread, initial intensity, location, etc.

TCON

TCON is a simple track consensus calculated by averaging the forecast latitudes and longitudes provided by the GHMI (interpolated GFDL), EGRI (interpolated UKMET with subjective quality control), NGPI (interpolated NOGAPS), HWFI (interpolated HWRF), and GFSI (interpolated GFS). All five model members must be present to calculate TCON. The member models forming the TCON consensus are evaluated annually, and may change from year to year.

TCCN

TCCN is a version of TCON that is corrected for model biases. The biases are derived statistically, based on parameters known at the start of the forecast, such as model spread, initial intensity, location, etc. The member models forming the TCCN consensus are evaluated annually, and may change from year to year.

TVCN

TVCN is a simple track consensus calculated by averaging the forecast latitudes and longitudes provided by the GHMI (interpolated GFDL), EGRI (interpolated UKMET with subjective quality control), NGPI (interpolated NOGAPS), HWFI (interpolated HWRF), GFSI (interpolated GFS), GFNI (interpolated GFDN model), and EMXI (interpolated ECMWF model). TVCN requires at least two of the seven member models to be present. The member models forming the TVCN consensus are evaluated annually, and may change from year to year.

TVCC

TVCC is a version of TVCN that is corrected for model biases. The biases are derived statistically, based on parameters known at the start of the forecast, such as model spread, initial intensity, location, etc. The member models forming the TVCC consensus are evaluated annually, and may change from year to year.

ICON

ICON is a simple intensity model consensus computed as the average of the forecast intensities from the DSHP (Decay-SHIPS), LGEM, HWFI (interpolated HWRF), and GHMI (adjusted GFDI) models. All four model members must be present to calculate ICON. The member models forming the ICON consensus are evaluated annually, and may change from year to year.

IVCN

IVCN is a simple intensity model consensus computed as the average of the DSHP (Decay-SHIPS), LGEM, HWFI (interpolated HWRF), GHMI (adjusted GFDI), and GFNI (interpolated GFDN). IVCN requires at least two of the five member models to be present. The member models forming the IVCN consensus are evaluated annually, and may change from year to year.

Florida State University Super Ensemble (FSSE)

The Florida State University Superensemble (FSSE) is a corrected multi-model consensus that uses both dynamical models and the previous official NHC forecast as the basis of its prediction. The FSSE employs the "corrected" consensus technique where individual model biases are computed based on the past performance of each member model, and the weights for each member model are determined using linear multiple regression during a "training phase". The "training phase" includes approximately 75 individual sets of past forecasts from each of the member models. The FSSE is constantly learning from the past performance of the models that comprise it. The FSSE technique is most accurate when no major changes are made to any of the member models between the "training phase" and operational forecast phase. The FSSE technique originated at Florida State University. NHC currently receives real-time FSSE output from a version of the technique provided by Weather Predict, Inc.

National Weather Service Global Ensemble Forecast System (GEFS)

The GEFS is an ensemble prediction system based on the GFS model. It consists of a low-resolution (approximately 105 km horizontal grid spacing with 28 vertical levels) control run of the GFS and 20 ensemble members at the same resolution. Uncertainties in the initial conditions are addressed by the use of a technique that generates different variations, or perturbations, in the initial states of each of the 20 member runs. Vortex relocation of TCs is applied to each member initial state, i.e., the starting locations of TCs are assumed to be well known and are therefore identical in the initial states of all ensemble members. The GEFS produces forecasts out to 16 days, four times per day. The mean of the 20-member ensemble forecasts is typically used as forecast guidance, however the individual ensemble runs can yield useful prognostic information as well. For instance, the variability of TC forecast tracks in the ensemble may provide insight on forecast uncertainty. It should be noted, however, that on average track forecasts produced by the GEFS have been less skillful than those produced by a multi-model consensus forecast. The GEFS can also be used for guidance on TC genesis. For instance, if a consensus of ensemble members predicts the formation of a TC, the forecaster may consider more seriously the prospect of TC development.

ECMWF Ensemble Prediction System (EPS)

The EPS is comprised of a low-resolution control run of the ECMWF global model (approximately 50 km with 62 vertical levels) with unperturbed initial conditions plus 50 perturbed members at the same resolution that are run from day 0 to day 10 followed by a further reduced resolution run (approximately 35 km with 62 vertical levels) out to forecast day 15 at 0000 and 1200 UTC. Perturbations of the EPS are generated using the singular vector approach (Buizza and Palmer 1995). For the tropics (30ºS to 30ºN), a special methodology that includes the effects of diabatic physics (Barkmeijer et al. 2001) is utilized to create the perturbations. In this respect, the EPS perturbations are likely more valid for forecasting TCs than those from the GEFS.

Barkmeijr, J., Buizza, R., Palmer, T.N., Puri, K., and Mahfouf, J.-F., 2001: Tropical singular vectors computed with linearized diabatic physics. *Quart. J. Roy. Meteor. Soc.*, **127**, 685-708.

Buizza, R., and Palmer, T.N., 1995:The singular-vector structure of the atmospheric global circulation. *J. Atmos. Sci.*, **52**, 1434-1456.

h. Trajectory Models

Trajectory models are much simpler than dynamical or statistical models as they merely move a TC along a track based on the prevailing flow derived from a dynamical model. While trajectory models utilize information from dynamical models to represent the prevailing flow, they do not allow the cyclone to interact with the surrounding atmosphere. Another limitation associated with trajectory models is their reliance on fixed levels in the atmosphere to represent the prevailing flow. To account for the variation in the prevailing flow with height, multiple versions of the same trajectory model based on varying depths are typically employed.

Beta and Advection Model (BAM)

The Beta and Advection Model (BAM) refers to a class of simple trajectory models that utilize vertically averaged horizontal winds from the GFS to compute TC trajectories. These trajectories include a correction term to account for the impact of the earth's rotation. The BAM is based upon the concept of a simple relationship between storm intensity/depth and steering levels. Strong cyclones typically extend through the entire depth of the troposphere and are steered by deeper layer-average winds, while weaker cyclones are steered by shallower layer-average winds. The BAM is run in three versions corresponding to the different depths used in the trajectory calculation: BAM shallow (850-700 mb), BAM medium (850-400 mb), and BAM deep (850-200 mb), known as BAMS, BAMM and BAMD, respectively. The performance of the BAM is strongly dependent on the dynamical input from the GFS. A divergence of the three versions of the BAM indicates varying steering flow within the parent GFS model. Hence, spread among the three versions of the BAM also serves as a rough estimate of the vertical shear as well as the complexity and uncertainty in the track forecast.

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